CHAPTER 6
STRUCTURAL SOLUTIONS

Section I. Ice Retention Methods

6-l. Introduction. An example of river ice management by ice control structures is found on the St. Marys River at Sault Ste. Marie, Michigan. The harbor there, called Soo Harbor, covers a large area, and immediately downstream from the harbor is a 600-ft-wide, man-made navigation channel, called Little Rapids Cut. Below the cut lies Lake Nicolet with its low velocity flows. The channel is dredged to a minimum depth of 27 ft, and ocean-going vessels and lake carriers of various sizes up to 1000 ft long use it. Ice broken from Soo Harbor by passing ships would accumulate in Little Rapids Cut so much that at times the river discharge was retarded and unacceptably high water levels would develop in the harbor. Also ferry traffic to an island community was frequently disrupted.

a. An ice-hydraulic-navigation model was made of this locale and tests were conducted. The tests showed the optimum location, orientation, and size for an ice control structure that acted mainly on the water surface. An ice boom with a 250-ft-wide navigation opening was designed, built, and installed in 1975 at the harbor end of Little Rapids Cut. Later, two gravity structures were set in the harbor upstream of the boom to inhibit some troublesome lateral movement that would develop in the 1-3/4-mile-long ice sheet that was retained by the boom. The booms and the structures were removed in the spring and reinstalled in the fall. Artificial islands eventually replaced the gravity structures. This work was done as part of a demonstration program that has been completed; the booms, however, continue to be used because they provide stability to the ice cover during storms and intermittent ship transits (Perham 1985).

b. The above situation is unusual for a river system because of the size of the harbor and the depth of the navigation channel. Most rivers have a 9-ft navigation depth and handle barge traffic almost exclusively (Perham 1988a). Harbors and fleeting areas for most navigable rivers are not found exclusively in bays and inlets, as are coastal seaports, but are instead found in almost any type of river reach, including the inside and outside of bends, at confluences, and in straight reaches. Structural ice control measures would most likely have to be located outside of the harbors and fleeting areas to permit free access of barge tows to moorings and wharfs and to accommodate cross-stream traffic (Perham 1988b).

6-2. Flexible Structures. The primary flexible ice control structures applicable to navigable rivers are ice booms. Another supplemental device with promise is called the line array, but it has only undergone experimental testing. A common characteristic of flexible structures is that they are installed, removed, and maintained using common maritime equipment, such as barges, cranes, winches, and tugs.

a. Ice Booms. Ice booms are the most widely used type of sheet ice retention structure. The first such structures were long booms of logs chained or wired end-to-end into a long line across a water

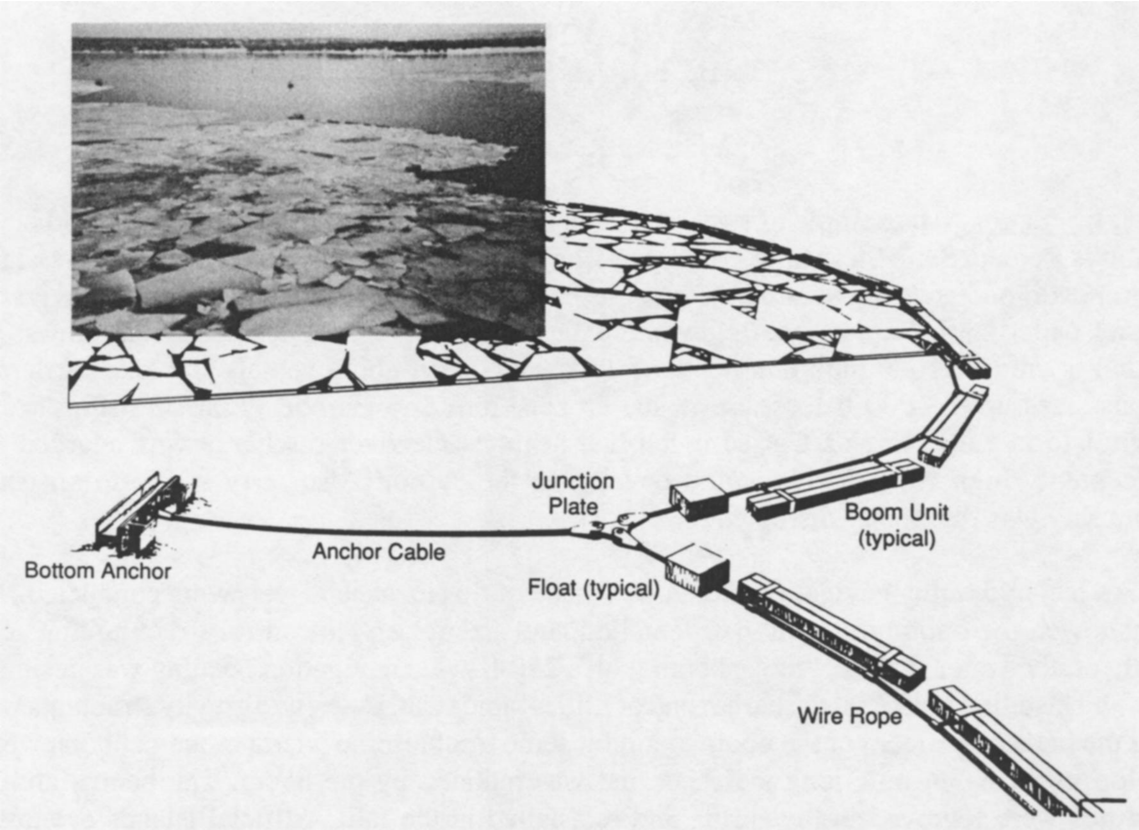


Figure 6-1. Typical ice boom arrangement.

body. The logs provided flotation as well as structural strength. Sometimes, several logs were bolted side by side to obtain sufficient flotation. The booms were anchored onshore and to boom docks (rock-filled timber cribs) in midstream. The trash booms used at hydroelectric plants to keep floating debris from power canals are similar and may have been the first to use a continuous wire rope for structural strength. The most common type of ice boom consists of large floating timbers held in place by a wire rope structure and buried anchors (Fig. 6-l). The weight of the wire rope connectors, anchor rope, and junction plates is carried by supplemental floats.

(1) Boom structures can be installed across a portion of a river or across the entire width, according to the amount of control needed. To be effective, an ice boom must restrain an ice cover at the surface without restricting water flow, and it must move up and down with the ice cover. The floating timbers intercept moving ice floes, frazil slush, and brash ice to form an unconsolidated ice cover upstream of the boom. In early winter the ice cover usually becomes consolidated within 10 days. An unconsolidated ice cover develops most rapidly and reliably when the water velocity (bringing ice floes to the boom) is as large as possible without causing appreciable quantities of ice to pass beneath the boom. Field tests show that this velocity for a straight, 9-ft-deep channel is 1.5 ft/s. This value is also optimum for the deeper (35 ft) but somewhat irregular Beauharnois Canal (a power and navigation canal in Canada). During the freezeup period, the flow on the

Beauharnois is reduced to approximately 1.6 ft/s to allow a smooth ice cover to develop. As the ice cover becomes solid, the canal flow is gradually increased until the flow velocity is returned to 2.2 ft/s and higher for efficient power generation. In several major boom installations the mean velocities vary from 0.95-2.75 ft/s, but during freezeup, attempts are made to keep velocities no greater than 1.5-1.6 ft/s.

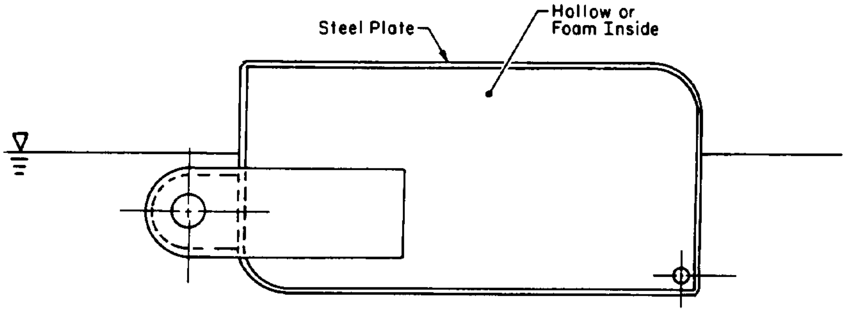
(2) Although ice booms vary in function and appearance, their wire rope structures are similar. The wire ropes to which the timbers or pontoons are connected are somewhat longer than the spacing between the anchors and anchor ropes, giving a boom its scalloped appearance. In existing booms these lateral ropes are longer than the span by values ranging from 6 to 25 percent; the greater length lowers the tension in the lateral rope. Individual wire ropes are connected by steel junction plates that are supported by buoys or floats. Galvanized wire ropes are often used for longer life, although the strength of the galvanized wire is 10 percent less than that of uncoated wire when new. However, for the Allegheny River Ice Boom at Oil City, Pennsylvania (discussed later), the Pittsburgh District chose stainless steel wire rope for long life. District personnel determined that the earlier anticipated replacement of galvanized wire rope, due to abrasion and subsequent corrosion, would exceed the higher initial cost of stainless steel.

(3) Figure 6-2 shows a variety of ice boom designs, The designs shown in Figures 6-2h, i, and k have been used as shear booms for waterborne trash and logs; the floating material is expected to slide along the upstream face of the boom. The proper combination of buoyancy and stability can be determined through tests and analysis. Wooden timbers can lose effectiveness with time by becoming waterlogged.

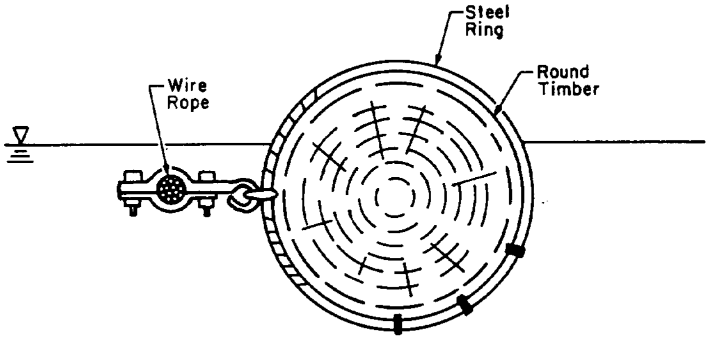
(4) Anchor types may vary on any one boom and from one boom to the next. They rely on the strength of the riverbed and bank materials. A structure that reaches from shore to shore will have anchors onshore and sometimes along the river bottom, depending on the expected loading. The length of the anchor lines from the river bottom to the floating parts is generally about 12 times greater than the water depth. Typical anchors are shown in Figure 6-3. The cell structure (Fig. 6-3c) is sometimes used at the midstream end of a spur boom, i.e., one that reaches only partway across a river.

(5) A representative list of flexible ice booms is given in EM 1110-2-1612. The largest boom to be installed in recent times is in Lake St. Francis on the St. Lawrence River, upstream of the Beauharnois Canal in Canada (Fig. 6-4). It was designed to accommodate ship navigation and was extensively tested as a model.

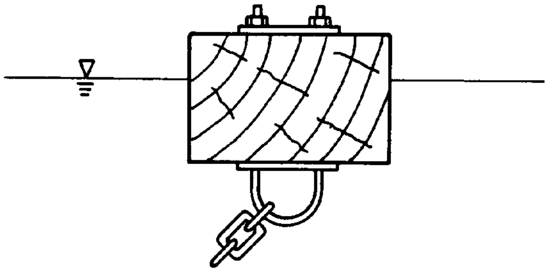
(6) Though not a navigation application, a similar design was used for the boom built by the Corps of Engineers in 1982 on the Allegheny River upstream of its confluence with Oil Creek at Oil City, Pennsylvania (Fig. 6-5). Oil City has along history of ice jams and floods that were caused by large deposits of frazil ice downstream of the confluence in a deep section of the river. The accumulations especially restrict flows from ice breakup on Oil Creek, which precedes ice breakup on the Allegheny River. The ice cover upstream of the boom stabilizes in early winter and eliminates the primary source of frazil ice. A boom of this type could be utilized to control ice from a tributary stream that otherwise would enter a navigable river.



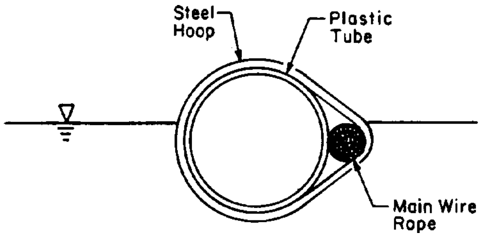
a. Rectangular pontoon boom.



b. Round timber boom.

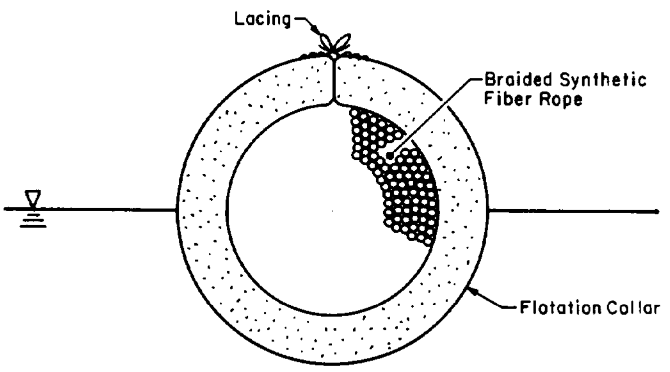


c. Single rectangular timber boom.

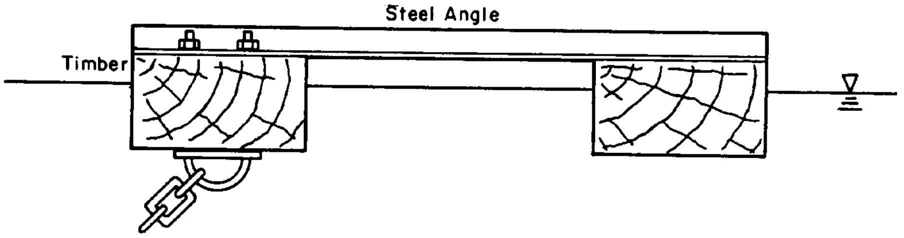


d. Plastic tube boom.

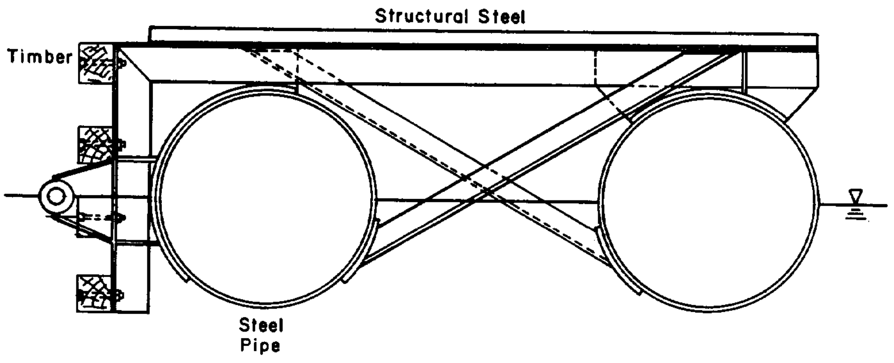
Figure 6-2. Cross sections of ice boom timbers and pontoons for a variety of ice boom designs.



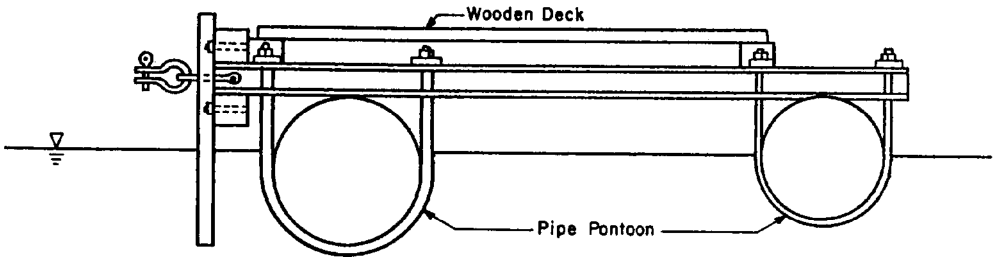
e. Synthetic fiber rope boom.



f. Double rectangular timber boom.

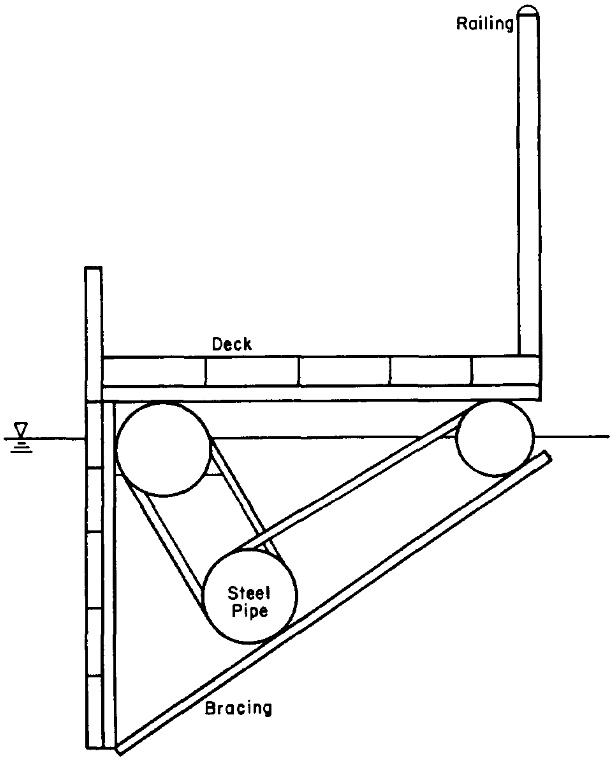


g. Double steel pontoon boom.

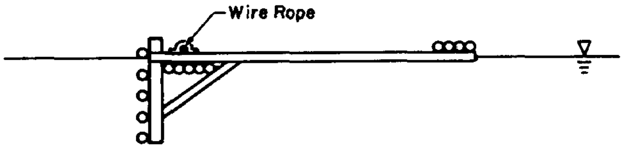


h. Shear boom.

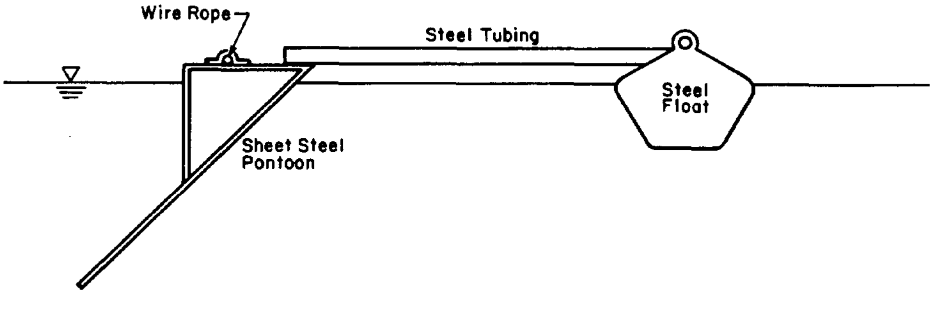
Figure 6-2 (Continued).



i. Shear boom.

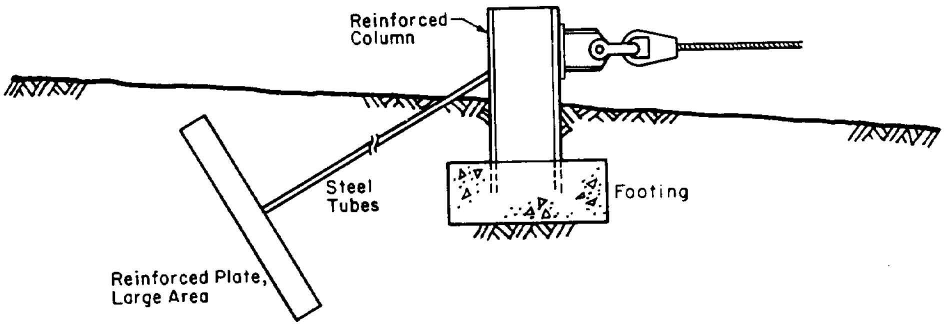


j. Wooden pole boom.

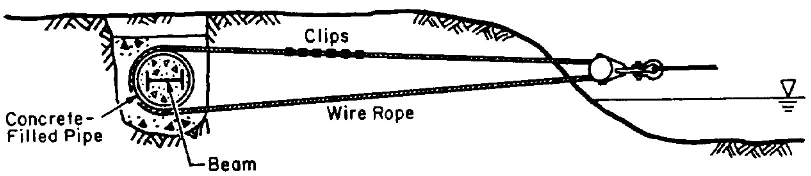


k. Triangular-skirted pontoon boom.

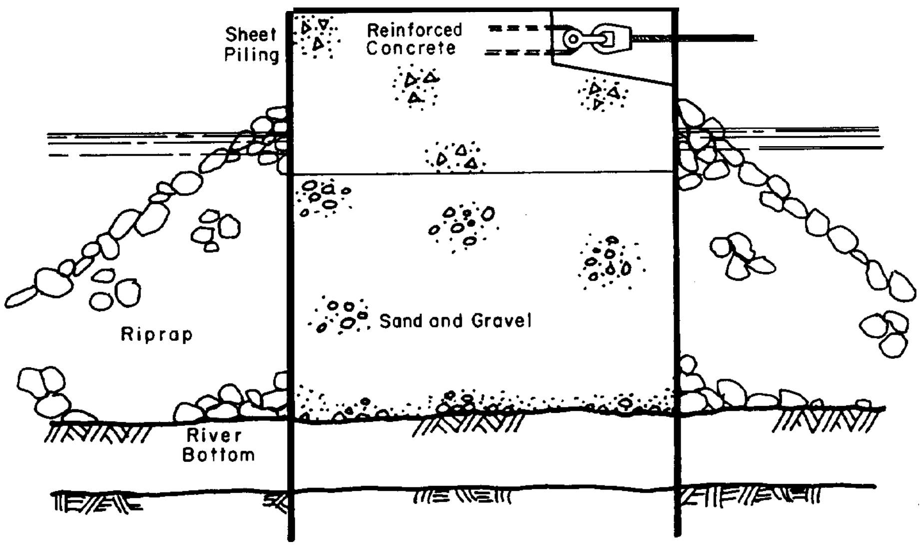
Figure 6-2 (Continued). Cross sections of ice boom timbers and pontoons for a variety of ice boom designs.



a. Deadman and pedestal (end, land).

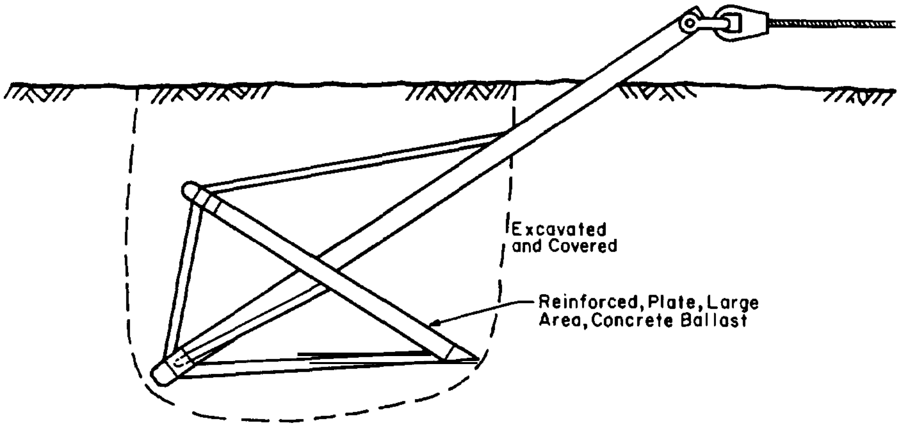


b. Deadman and wire rope (end, land).

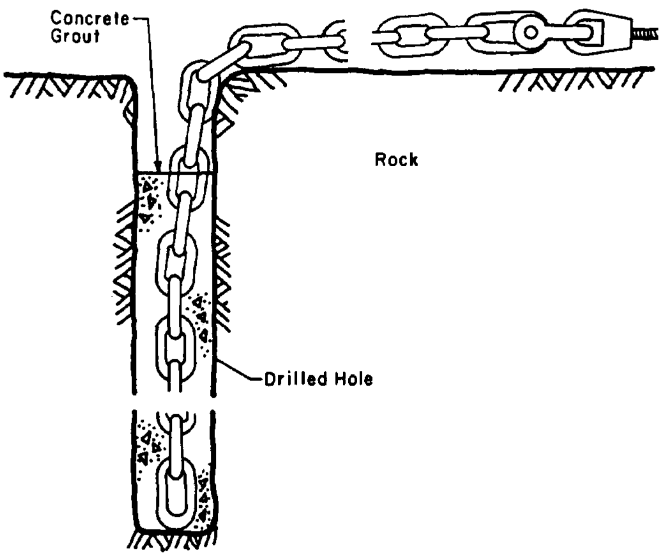


c. Sheet piling cell (end, in water).

Figure 6-3. Typical ice boom anchors.

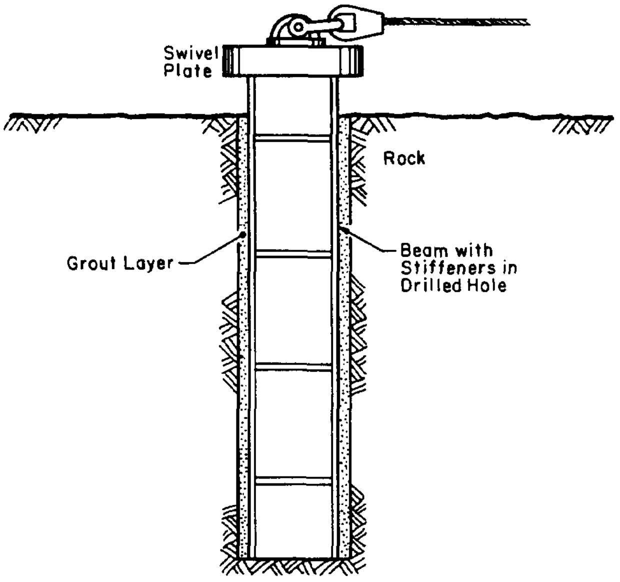


d. Steel anchor (midpoint, in water).

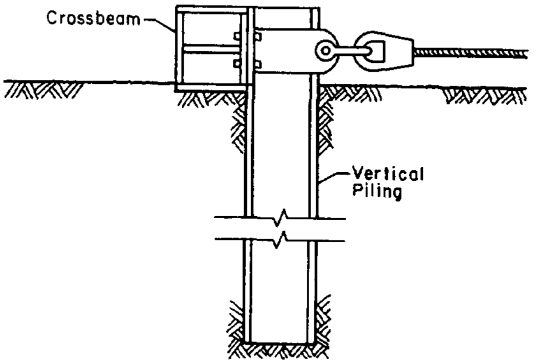


e. Grouted chain (midpoint, in water).

Figure 6-3 (Continued). Typical ice boom anchors.



f. Grouted weldment (midpoint, in water).



g. Piling and crossbeam (end, midpoint, land, in water). Two or more are needed.

Figure 6-3 (Continued).

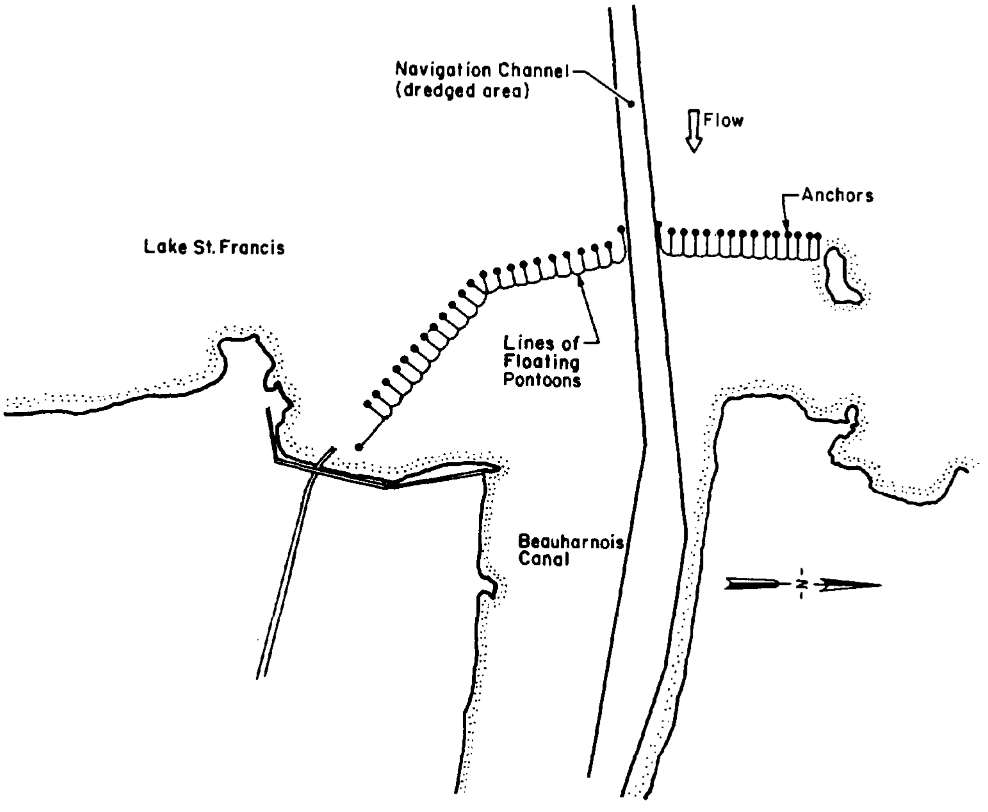


Figure 6-4. Plan view of the Lake St. Francis ice boom built in 1981.

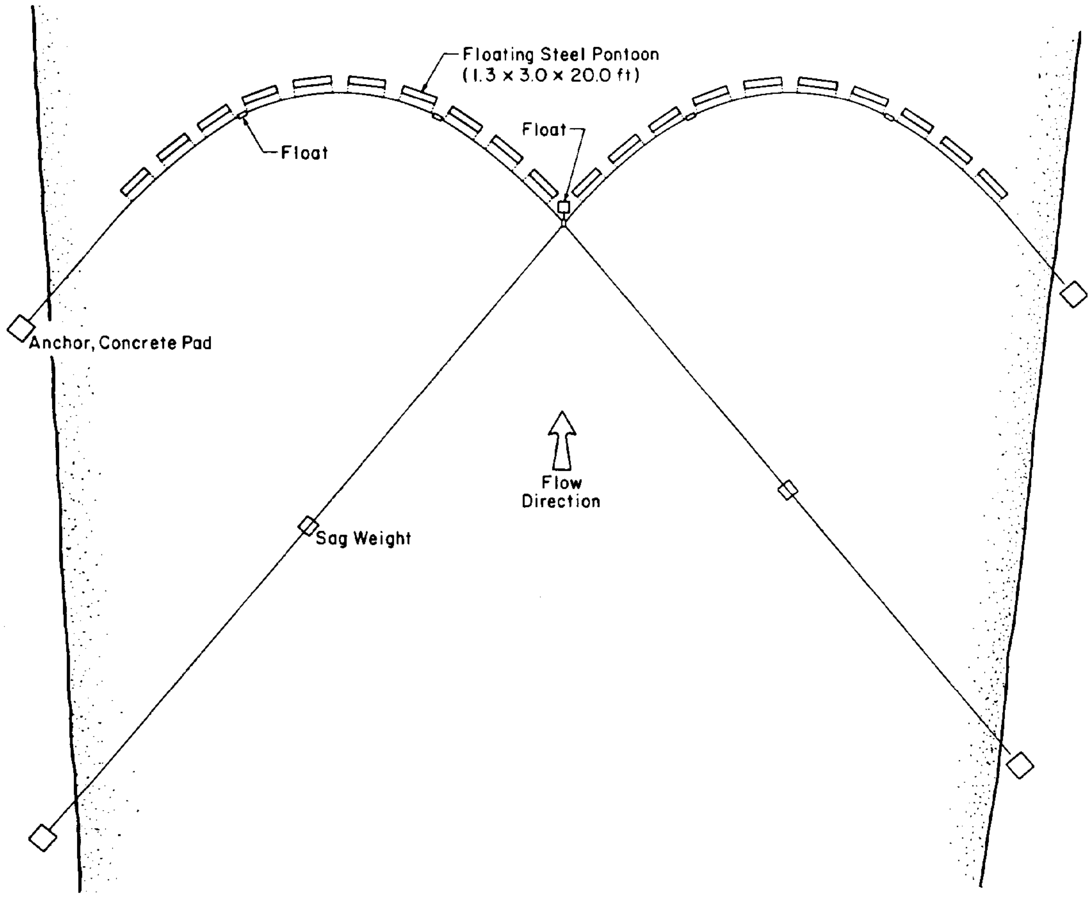


Figure 6-5. Plan view of the Allegheny River ice boom built in 1982.

b. Line Arrays. These devices are still experimental. Arrays are made from nylon, polypropylene, polyester, or wire rope. Arrays of buoyant lines may be used to stabilize existing large ice sheets by holding them in place against flow forces after they crack free from shore. The lines can expand the area that a buoy, or a timber, is expected to reliably influence. An example is shown in Figure 6-6. Such cracks can result from water level changes, ship passages, or warm water discharges. Also, several sets, probably without the shore anchors shown in Figure 6-6, have the potential for delaying spring ice movement on a section of river. The loss of a device like this during ice breakup is always a possibility, and the consequences of this loss must be considered (also see EM 1110-2-1612).

6-3. Rigid or Semi-Rigid Structures. Rigid or semi-rigid structures may or may not have moving parts. They are appreciably more rigid than a typical ice boom, but their deflection in response to the horizontal push of an ice sheet is on the same order as the deflections that develop in the ice sheet itself. Because these structures are generally unyielding, they are particularly susceptible to ice sheet impact and thermal expansion loads. The state of the art in design today is generally based on the conservative values of load and stress developed for dams and bridges. A list of rigid or

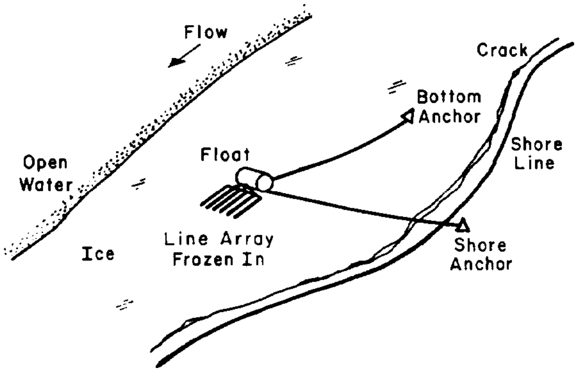


Figure 6-6. Line array anchoring an ice sheet that has cracked free from shore.

semi-rigid structures is given in EM 1110-2-1612. Only the structures in this category that have actually been used for navigation ice control will be discussed in this manual. Several of the others, however, have been seriously considered for navigation purposes.

a. Ice Piers. Ice piers are structures set in the river to protect a fleeting area against moving ice. The piers take the brunt of the impact and pressure forces and either stop the ice or deflect it to move around the ice pier location. Barges and tows are anchored downstream of the ice piers, which have anchoring chains for this purpose. The piers may be rectangular reinforced concrete structures, 16 x 25 x 10 ft high above water, or they may be similar to cylindrical sheet piling cells as in Figure 6-7.

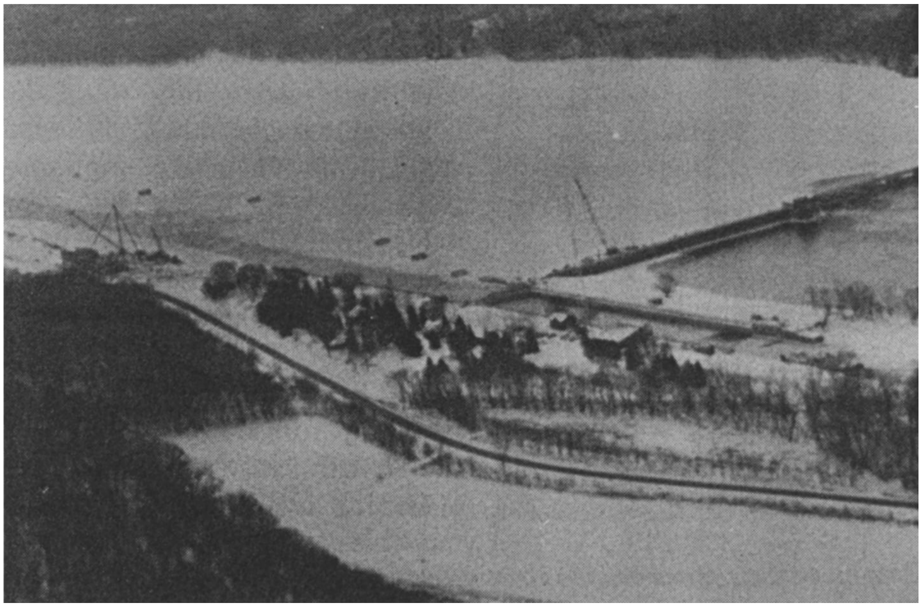


Figure 6-7. Cylindrical sheet piling mooring cells upstream of a navigation dam can help to stabilize the ice cover in winter.

b. Drift Deflectors.

(1) A drift deflector is usually a barge or barges set on a diagonal with one end against the shore to deflect material floating with the currents outwardly away from shore. This method is seen to work well on the inside of bends where the normal water currents have a natural component away from the shore. A fleeting area immediately downstream could be protected by a drift deflector.

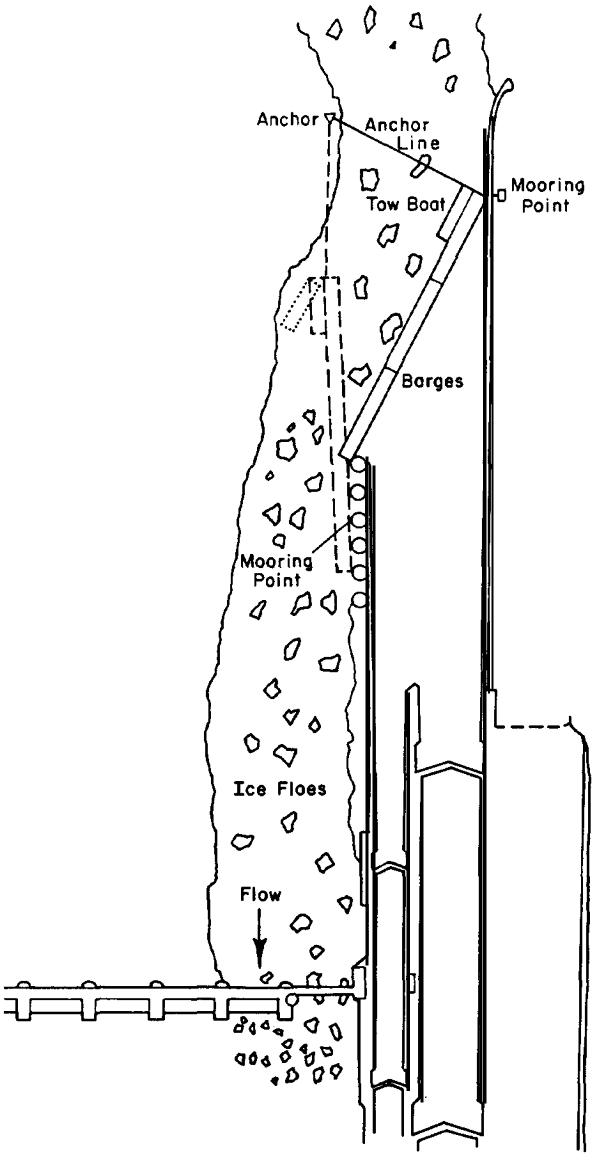


Figure 6-8. Diagram of a proposed movable ice deflector composed of three barges and a towboat, which could be deployed to protect an upper lock entrance from ice accumulation.

(2) A large ice deflector arrangement was proposed for installation (but not built) at Montgomery Locks and Dam, on the Ohio River, to reduce the amount of ice entering the lock during winter navigation. As shown in Figure 6-8, three barges and a mechanical linkage type of anchoring were proposed. A towboat was to move it between its open and closed positions and also break ice. A similar function is sometimes provided by barge tows on the Mississippi River waiting for lockages at Chain of Rocks Canal and at Lock and Dam No. 17. Ice passage at these sites is no problem.

c. Artificial Islands. In the same manner that natural islands help hold ice in place, artificial islands can be used to help form, stabilize, and retain an ice cover in certain locations. One example is the Lake St. Peter section of the St. Lawrence River, about 50 miles downstream of Montreal, Canada (Fig. 6-9). Lake St. Peter is about 8 miles wide and 20 miles long and has an average depth of 10 ft. Passing through the middle of the lake is a 800-ft-wide navigation channel dredged to a depth of 35 ft. The water flow velocity in most of the lake averages about 1.0 ft/s, while in the channel it is 1.6 ft/s.

(1) To prevent floods in Montreal Harbor, a passageway for ice floes, slush, and frazil ice is maintained by icebreakers from Montreal Harbor to Quebec City. At times, however, ice sheets would break free and be moved by wind and water to clog the passageway. Occasionally, a strong northeast wind would move the floating ice back upstream. Some light-tower bases helped hold the ice, but more stabilization was needed.

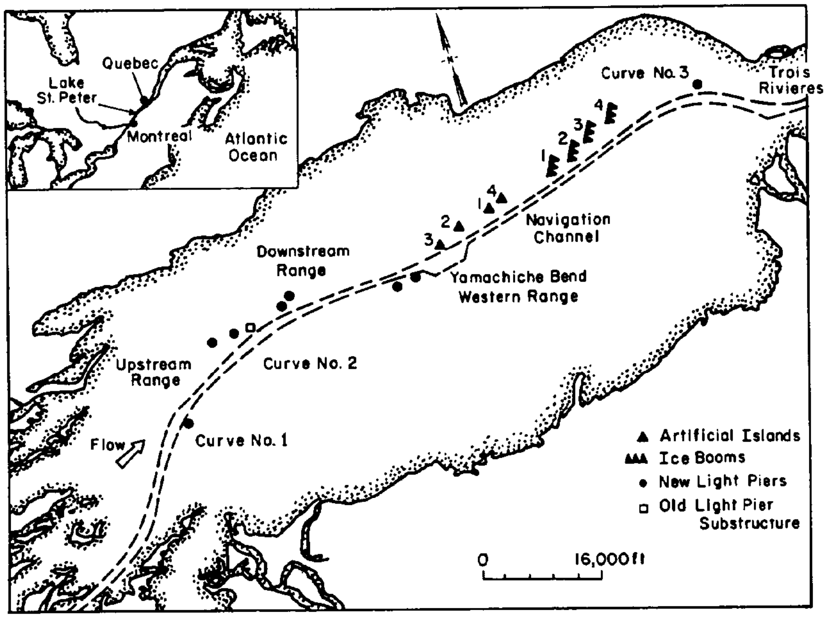
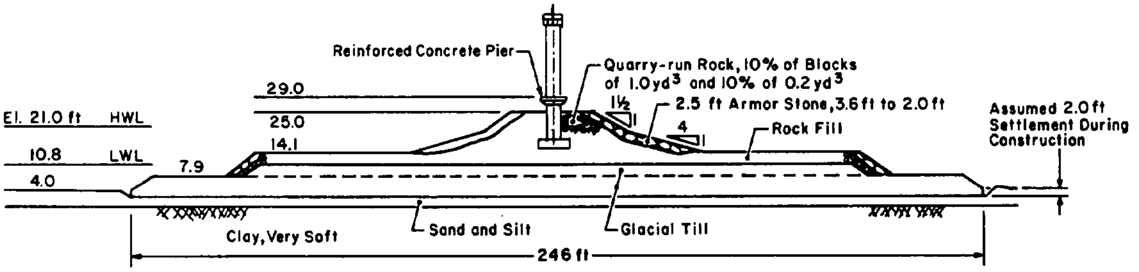
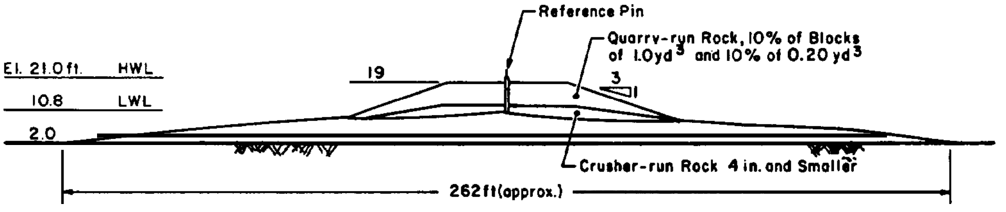


Figure 6-9. General plan and location of artificial islands, ice booms, and light piers in Lake St. Peter, St. Lawrence River.

(2) Several ice control structures were evaluated in various parts of Lake St. Peter and at Lavaltrie upstream in the river. Ice booms were successful but pile clusters did not perform well because the lake bed was probably too weak for the pilings to sustain the high ice forces. Artificial islands of three types were built to anchor the ice cover. The most stable type for the existing conditions is shown in Figure 6-10a. The second type (Fig. 6-10b), which cost much less to build, is only as high as the mean winter high water level. A third type was formed by placing riprap



a. High-type.



b. Low-type.

Figure 6-10. Cross sections of artificial islands in Lake St. Peter.

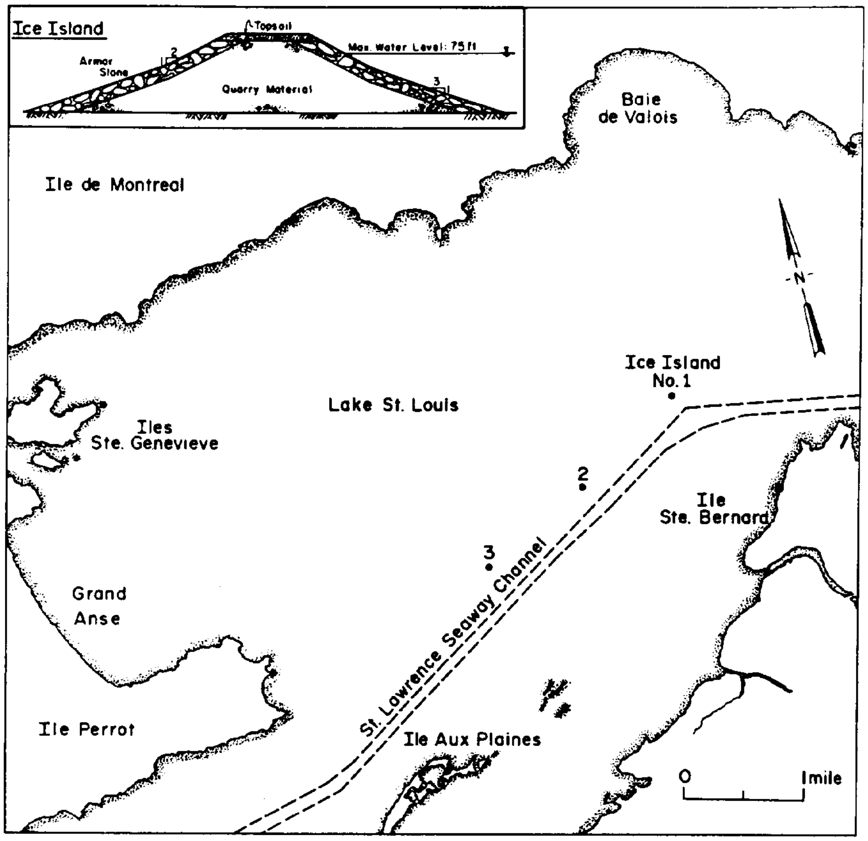


Figure 6-11. Artificial islands in Lake St. Louis, St. Lawrence River.

around the substructures of old light piers. The islands were successful in forming and retaining a stable ice cover, and the winter navigation season was increased by an average of 30 days. The islands, especially the low ones, require maintenance because the foundations have settled and the slopes have been eroded by moving ice.

(3) In 1980 three artificial islands were constructed in Lake St. Louis on the St. Lawrence River, upstream of Montreal. The islands are permanent and located east of Ile Perrot and north of the navigation channel (Fig. 6-l 1). The islands were designed and constructed to help stabilize the ice cover north of the navigation channel, particularly during the spring breakup and the opening of the navigation season, eliminating the problem of large ice floes obstructing navigation. The effectiveness of the artificial islands has not been fully assessed.

(4) Artificial islands have been helpful in some locations, but they were chosen only after the ice movements had been studied. These islands provide good lateral stability to the ice cover, but a small change in water elevation will fracture the ice near the islands. Ice on the lee side may move away from the island, but ice on the windward side will remain in position. Islands armored with stone cost more initially but have lower maintenance costs.

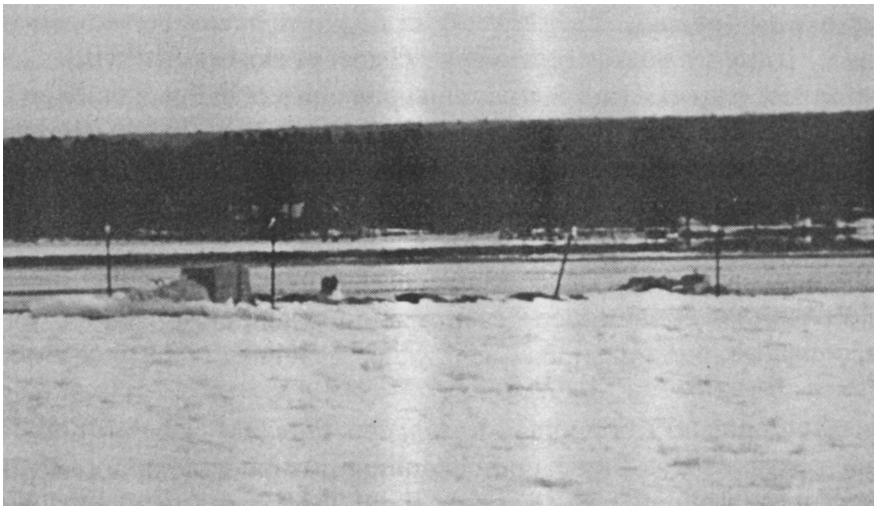


Figure 6-12. Rock-filled scow stabilizing the ice cover in Soo Harbor, Michigan.

d. Removable Gravity Structures. A problem developed with the St. Marys River ice control boom in the harbor at Sault Ste. Marie, Michigan, because the ice cover above the boom would break free from shore and move laterally into the open ship track. Although the loads from the ice sheet were within the expected range, their distribution was different enough to cause damage when the boom timbers were frozen solidly into the ice cover. Damage could be prevented if the ice cover could be kept from rotating. The only method that could be used at that time was a removable gravity structure. The main structure used was a scow, surcharged to a total weight of 270 tons and sunk in shallow water (Fig. 6-12). The scow was also secured with ship anchors. In the spring it was refloated and moved away. The method has worked very well.

(1) Later, observers noticed that sewage plant effluents weakened part of this ice cover on the St. Marys River. Thus, the ice-holding capability of the scow was supplemented by placing a stack of crane weights in the shallow water of Soo Harbor, about halfway between the scow and the ice boom. The reinforced concrete crane weights key together when stacked and are bound into a unit by wire ropes. The six crane weights weigh a total of 95 tons. They helped to reduce the rotating ice sheet problem to a manageable level.

(2) The holding force available from gravity devices depends not only on the weight of the device in water but also on the coefficient of friction between the device and the bottom; a value of 0.3 was used in the Soo Harbor analysis. The force level was estimated from the expected action of water and wind drag on the maximum expected ice sheet. Eventually, all the removable devices in Soo Harbor were replaced by artificial islands.

e. Pilings and Dolphins. Piles that support a wharf or pier can anchor or retain an ice sheet. The effects of the vertical uplifting forces and horizontal forces from ice sheets must be considered for structures using exposed pilings. Piling clusters, or dolphins, have received greater consideration for restraining ice. These are usually formed by a cluster of closely driven piles secured at the top with wire rope. Model tests of a line of individual pile clusters indicate that good ice retention is possible. An installation of several timber clusters in Lake St. Peter in 1962, however, failed early in winter. The cause was attributed mainly to a very weak foundation and large ice forces. Tests show that dolphins have surprisingly little resistance to steady lateral pulls.

(1) A dolphin in the Cap Cod Canal, Massachusetts, resisted ice action for several years but eventually failed from the action of ice floes moving in water currents with velocities up to 10 ft/s. The replacement dolphin in the 33-ft-deep water was made of 21 steel H-piles.

(2) Besides vertical and horizontal forces, the effect of ice abrasion is an important consideration. It is possible for ice to sever timber pilings in a matter of hours. Oak pilings are fairly ice resistant, but timber structures may last only about 20 years, partly as a result of ice abrasion. Timbers can be protected by steel armor. Concrete can also be adversely affected by ice abrasion and by the spalling of material from repetitive freezing and thawing of ice on its surface.

6-4. Structures Built for Other Purposes. The formation and retention of ice covers can be aided by structures that were not built for that purpose. Flows over hydroelectric dams can be manipulated to help an ice cover form. Other structures, such as wicket dams and bridge piers, aid in the formation and retention of ice covers simply by their presence.

a. Hydroelectric Dams. It is possible to aid the formation of an ice cover on a river by increasing flow depths and decreasing flow velocities at strategic times during the early winter. This capability must be accompanied by a comprehensive understanding of the hydraulics and ice conditions on the river, and how the river responds to various meteorological influences. Usually, ice-sheet retention structures are needed, too.

b. Wicket Dams. A wicket dam is composed of a series of rectangular elements or wickets that are propped side-by-side and on-end to form a sloping dam face (Fig. 6-13). A typical wicket is 1 ft thick by 3-1/2 ft wide by 16 ft long. The elements are raised and lowered by a barge-mounted crane, and usually they increase the upstream water level from 6 to 12 ft. They have been used on rivers such as the Ohio and the Illinois for maintaining the water levels needed for navigation during times of low flows. In this way they intrinsically help to form and maintain an ice cover.

c. Light Piers and Towers. Light piers and towers are used to mark the locations of navigation channels and courses. These structures can be built on land, but many are built offshore, where they become frozen into the ice sheet. Should the ice sheet break free from shore, a high force can be applied to the pier or tower. If the force is great enough, either the ice or the tower will yield. A drawing of a light pier built in Lake St. Clair near Detroit, Michigan, is shown in Figure 6-14.

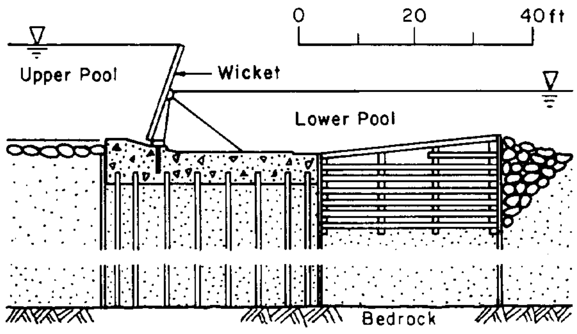


Figure 6-13. Typical section of a navigable pass portion of a wicket dam.

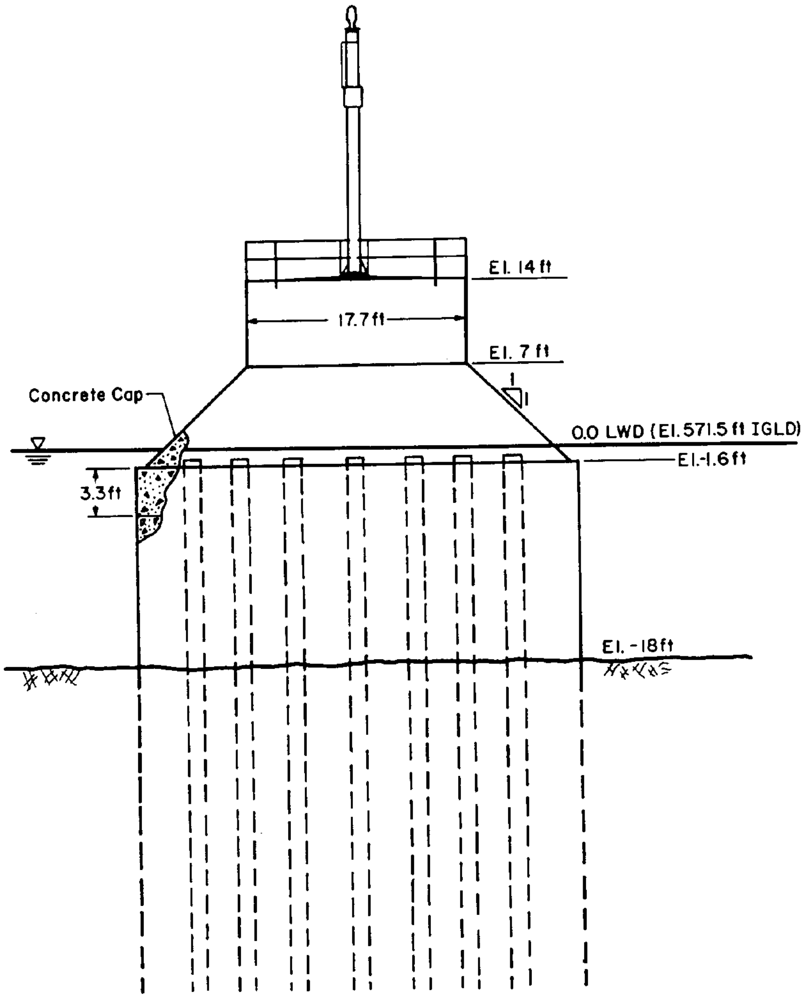


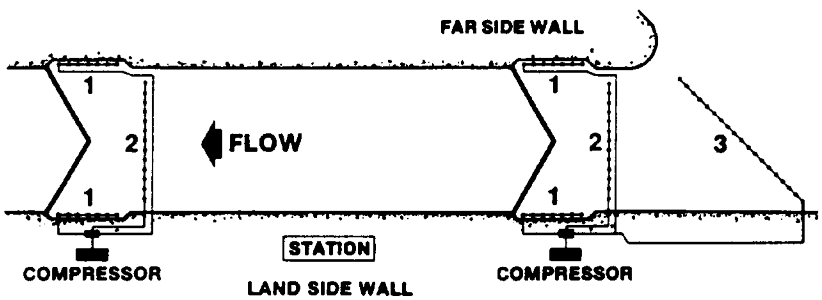
Figure 6-14. Light pier in Lake St. Clair, Michigan.

d. Bridge Piers. Bridge piers often constrict the river flow, and ice floes may collect at the piers in early winter to form an unconsolidated ice cover. Border ice growth on the piers can increase this narrowing effect at the water's surface if the spacing is small. Under some circumstances, however, this channel narrowing may lead to water velocities that are too high to allow an ice cover to form. Dynamic, static, and thermal ice pressures and ice abrasion must be considered in designing bridge piers.

Section II. Ice Control at Locks

6-5. General. Ice problems at locks have been identified and grouped into six categories. These are discussed in Chapter 3. Ice adhering to various lock surfaces and floating brash ice hinder normal lock operations and can delay barge movements for hours. The most notable problem with brash ice is its accumulation in the gate recess area, so that the gates cannot be completely opened. The most successful way to disperse ice is by means of high-flow air systems. These systems have up to three separate components (discussed below), each with a specific function that increases the ease of lockage operations.

6-6. High-Flow Air Systems. Air manifolds should be placed in three specific locations around a lock to completely mitigate the problems of brash ice (Fig. 6-15). First, a recess flusher should be placed in each gate recess; this will clear the recess area. The second manifold, called the screen, should be located just upstream of each set of miter gates. At the upstream edge of the gate forebays, there is typically a sill that runs across the lock chamber; place the screen on the downstream side of that sill. This screen keeps brash ice from entering the lock or, in the case of



1. RECESS FLUSHER
2. SCREEN
3. DEFLECTOR

Figure 6-15. Schematic diagram of a complete high-flow air system, showing the three locationsfor air manifolds at a typical lock. Two compressors are shown, but one large compressor with long supply lines could also be employed, assuming the supply lines are adequately sized.

the downstream screen, clears ice from an area across the width of the chamber before the gate recess flushers are used. The third component is an optional one, depending on the physical layout of the lock and dam project. When there is some means for passing ice through or over a nearby spillway, the addition of a diagonal deflector in the upper lock approach can be an effective way to direct the floating ice toward the spillway. This manifold is typically installed using divers and weights because the area cannot normally be dewatered.

6-7. High-Flow Single-Point Bubbler. Single orifices can be placed on the back wall of a floating mooring bitt recess. A single air line discharging at the bottom of the recess provides sufficient water turbulence to prevent floating ice from being pushed and packed between the float and the recess walls.

6-8. Air System Components. Each of the major components of high-flow air systems are discussed to clarify what is required and to provide information on physical size and placement of the components.

a. Compressor. The air compressor of the size required is generally either diesel-powered or electrically operated. It can be either a permanent fixture or rented for the winter months. In a complete high-flow air system, the component requiring the most amount of air is the diagonal deflector. For a 110-ft wide chamber, a diagonal deflector manifold length of at least 200 ft is required. Design calculations (Para. 6-10) will indicate that a compressor of at least 750-ft3/min capacity must be available. No more than one manifold should be used at any one time.

b. Supply Lines.

(1) Pipes that run from a single, centrally located compressor to each end of the lock chamber must be large enough to handle the necessary air flow. One of the most common mistakes in designing an air system is undersizing the supply lines. Typically, at least a 3-in.-diameter schedule 40 pipe should be considered. If a supply length of over 500 ft is required, then a 4-in. pipe should be used for at least part of the total distance. Air control valves should be located at each end of the lock. Ideally, they should be remotely operated for easy use by the lock operator. The control valves allow the operator to selectively choose which air manifold to operate at any given time. An indicator should be provided to assure the operator that the valves are operating correctly.

(2) Supply lines from the control valves to the air manifolds submerged in the lock chamber vary in size, depending on the location of each manifold. The gate-recess flusher manifolds on the land wall require only a 2-in. pipe as a supply line (Fig. 6-16). The gate-recess flusher manifold on the river wall, because of the added distance across the lock chamber to the manifold, needs to have at least a 3-in.-diameter supply line until the supply line reaches the far side of the lock chamber. The air screen going across the forebay sill requires at least a 3-in. supply line because of the volume of air being delivered (Fig. 6-17). The location and placement of the supply lines may vary from lock to lock. It is best if the pipes can be located within the concrete walls, but if this is not possible, they should be located along the upstream edge of the gate-recess wall, protected from floating ice by steel plating.

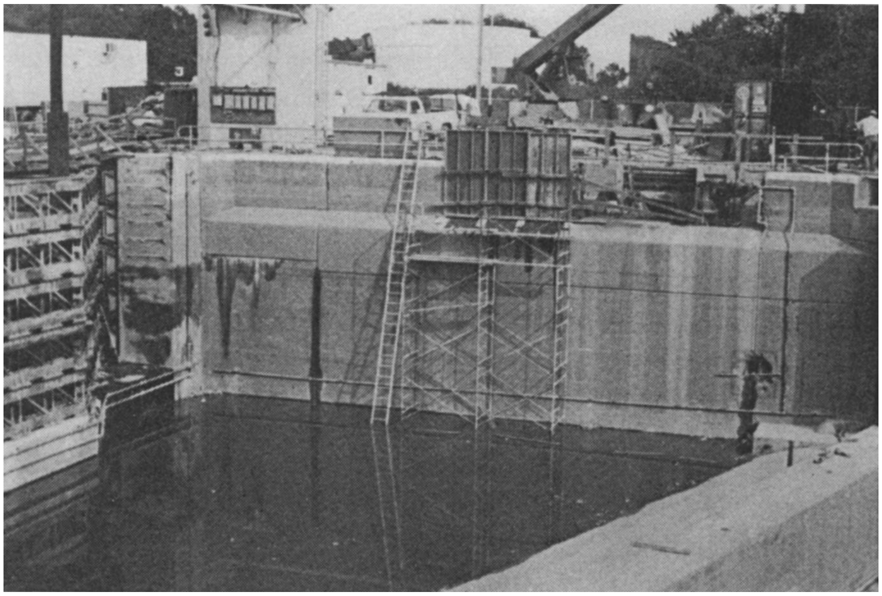


Figure 6-16. A flusher on the land wall of the upper gate recess composed of a supply line and the manifold with orifices at Peoria Lock on the Illinois Waterway. Note also the vertical supply lines for the recess flusher of the river wall gate and for the cross-chamber ail screen installed on the downstream-facing surface at the left (upper) end of the gate recess.

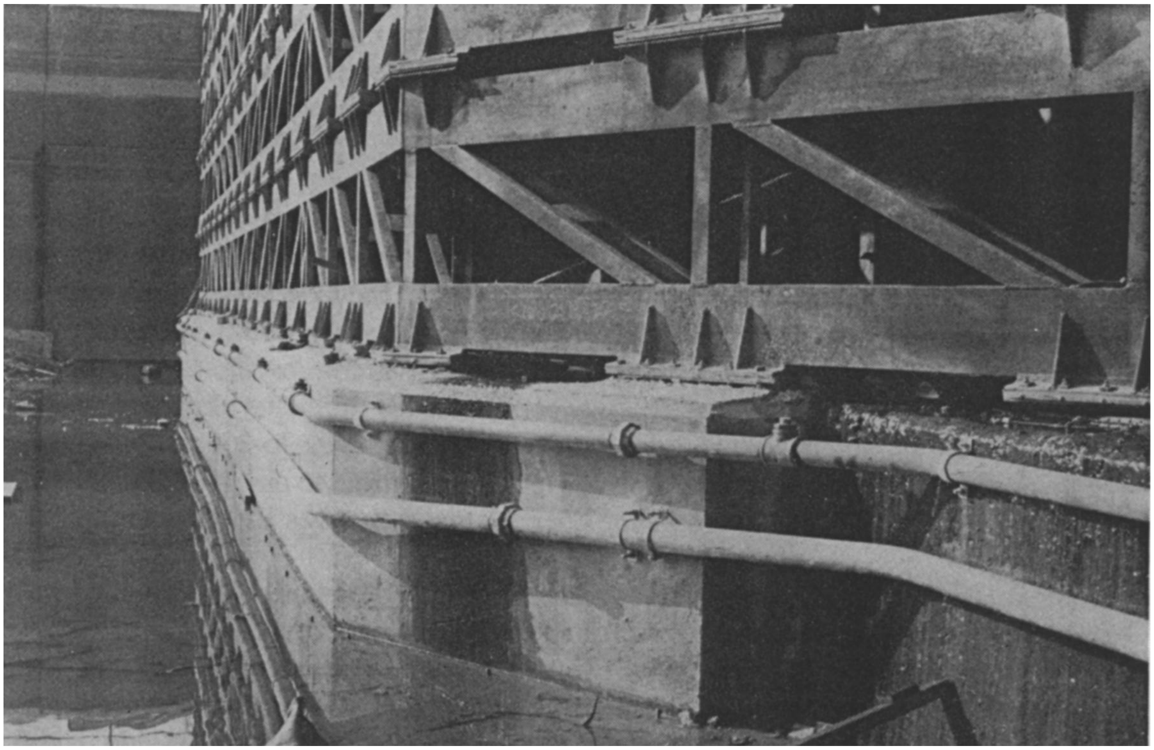


Figure 6-17. Downstream side of forebay sill, Peoria Lock. Air-screen manifold (top pipe) and supply line for river wall gate-recess flusher (bottom pipe) are attached to the sill face with U-straps. There is an orifice at each pipe tee location in the manifold.

c. Check Valves. At the bottom of the vertical leg of each supply line entering the lock chamber, an in-line, spring-loaded check valve should be installed to prevent water from passing into the manifold through the orifices, entering the supply pipe, and freezing near the water surface when the air lines are shut off. This check valve must be removable by divers for replacement or repair if required.

d. Manifolds. The manifolds for each of the systems vary with the number of orifices and the size of the pipe. The design of an air manifold should provide for an even and uniform air flow through its entire length. To achieve this goal, the total area of the orifices must be less than 25 percent of the cross-sectional area of the manifold.

e. Recess Flushers. The gate-recess flusher manifold differs from the other air manifolds because of the orifice spacing and pipe size. Laboratory and prototype analyses have shown that the spacing of the orifices should vary to provide more air near the quoin or pivot of the gate. The nominal spacings between orifices starting at the quoin end of the gate should be 4,4,4,6,8,10, 10, and 10 ft. The actual length of the manifold may vary because of lock constraints. Typically, in the locks on the Illinois Waterway, nine orifices are used.

f. Screens. The manifolds for the sill screens are designed with an 8-ft orifice spacing. For locks with a width of 110 ft, a 96-ft-long manifold is used; 13 orifices are placed along that manifold.

g. Deflector. For a diagonal deflector in the upper lock approach area, a 200-ft manifold is recommended, with 26 orifices.

h. Orifices. Each orifice is a drilled hole in a hex-head stainless steel pipe plug, which is installed in a pipe tee in the manifold line. The inside of the plug is slightly chamfered, and there is a sharp edge at the outside surface. The orifices are aligned so that the air discharges vertically. Occasionally, the orifices might become plugged with silt, so the manifold should be regularly operated throughout the year to help the orifices remain free of dirt. The orifice diameter ultimately controls the amount of air discharged. From laboratory analysis, it is recommended that a design flow of 30 ft^3/min be provided for each orifice. This will provide sufficient air to create the desired effect at the water surface. For all the systems installed on the Illinois Waterway, 3/8-in.-diameter holes were drilled in the pipe plugs to serve as the orifices.

6-9. Effectiveness of the Air Systems. Experience gained from the use of complete high-flow air systems, as described above, has shown that the systems reduce winter lockage times, make for a safer operation, and keep the morale of lock personnel high. An average of one hour of compressor time is required to lock through an average tow. Some variation is experienced between individual operators, but all agree that a high-flow air system is an effective way to control floating ice problems at a lock (Fig. 6-18 and 6-19).

6-10. Design of a High-Flow Air System. The parameters affecting the design of a high flow air system include: air volume and pressure available, effective length and size of the supply line,

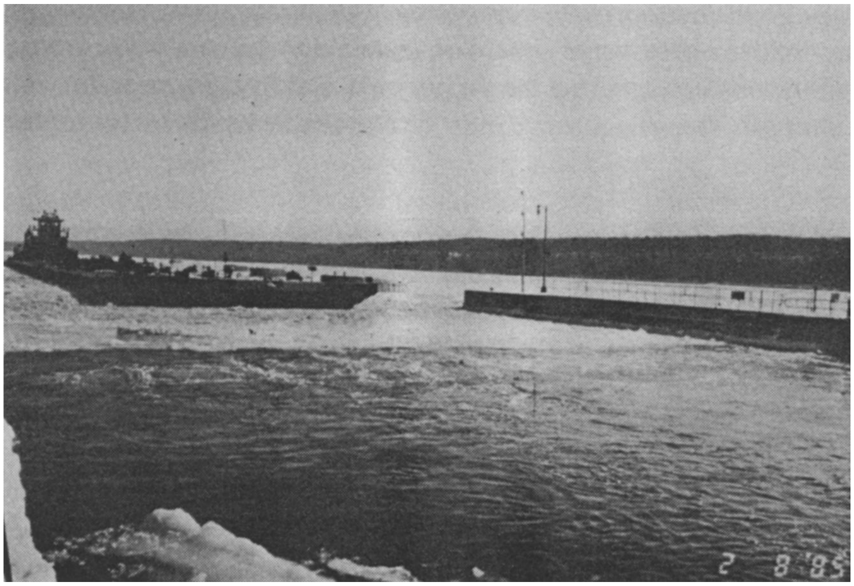


Figure 6-18. Upper screen in operation at Starved Rock Lock, Illinois Waterway. Most brash ice is prevented from entering lock chamber, even with the entry of downbound tows.

Figure 6-19. Gate-recess flusher in operation at Starved Rock Lock. The ice is flushed away from the recess area, allowing the miter gate to be fully opened.

length and size of manifold line, depth of submergence, orifice size, and orifice spacing. The air system analysis determines air discharge rates from an orifice by an iterative scheme that starts with a trial dead-end pressure. The analysis calculates the orifice discharge and pressure, starting from the end and working toward the supply point. After all the orifices are analyzed, the supply line pressure and air flow are calculated, The compressor pressure and flow rate necessary to sustain the supply line pressure and air flow are then calculated. The calculated compressor output is compared to the actual compressor output. The trial dead-end pressure is then adjusted and the analysis scheme repeated until the calculated and specified compressor outputs differ by no more than 1 percent. Changes in system parameters are made until the optimum design is obtained.

a. The calculations for optimizing the air system parameters are provided below. The initial trial dead-end pressure (P_d) is taken as:

$$P_d = P_w + \frac{(P_c - P_w)}{4} \tag{6-1}$$

where P_c = true compressor pressure
P_w = $\rho_w g H$ = hydrostatic pressure
ρ_w = mass density of water
g = gravitational constant
H = submergence depth.

The subsequent trial dead-end. pressure (P_d) is determined by:

$$P_{d\,(new)} = P_w + \left(P_{d\,(old)} - P_w\right)\left[\frac{P_c - P_w}{P - P_w}\right] \tag{6-2}$$

where
P = calculated compressor pressure
$P_{d(old)}$ = old trial dead-end pressure
$P_{d(new)}$ = new trial dead-end pressure.

The air discharge rate (Q_o) from the orifices is calculated by the discharge equation:

$$Q_o = C_d \frac{\pi d^2}{4} \sqrt{2\Delta P/\rho_a} \tag{6-3}$$

where C_d = discharge coefficient, sharped-edged circular orifice
d = orifice diameter
ΔP = pressure difference between inside and outside of diffuser line
ρ_a = mass density of air.

Finally, the pressure drop due to friction between orifices and in the supply line(ΔP_f) is calculated using the friction loss equation for turbulent flow conditions:

$$\Delta P_f = \frac{f \rho_a \ell v^2}{D 2g} \tag{6-4}$$

where f = friction factor
ℓ = equivalent length of pipe
v = air velocity
D = pipe diameter.

b. A computer program analyzing diffuser lines and nozzles gives a numerical simulation of air bubbler systems, and is used for the air screen analysis. The input data include: diffuser line length and diameter, supply line length and diameter, orifice diameter and spacing, nominal compressor

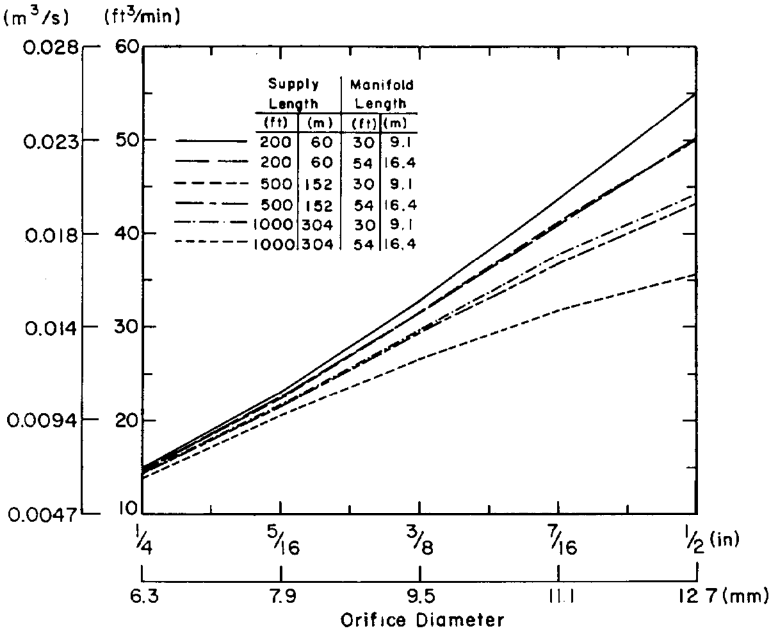


Figure 6-20. Performance curvesfor gate-recessflushers, showing the average air discharge from each orifice plotted with respect to orifice diameter, for combinations of three supply-line lengths and two manifold lengths. The 2-in. diameter manifolds are either 30-ft nominal length for 56-ft wide locks, or 54-ft nominal length for 110-ft wide locks, submerged 2O ft below the water surface. Six orifices at nominal spacings of 4,4,4,6, and 8 ft are present in the 30-ft manifolds, and three additional orifices at nominal 10 ft spacings are present in the 54-ft manifolds.

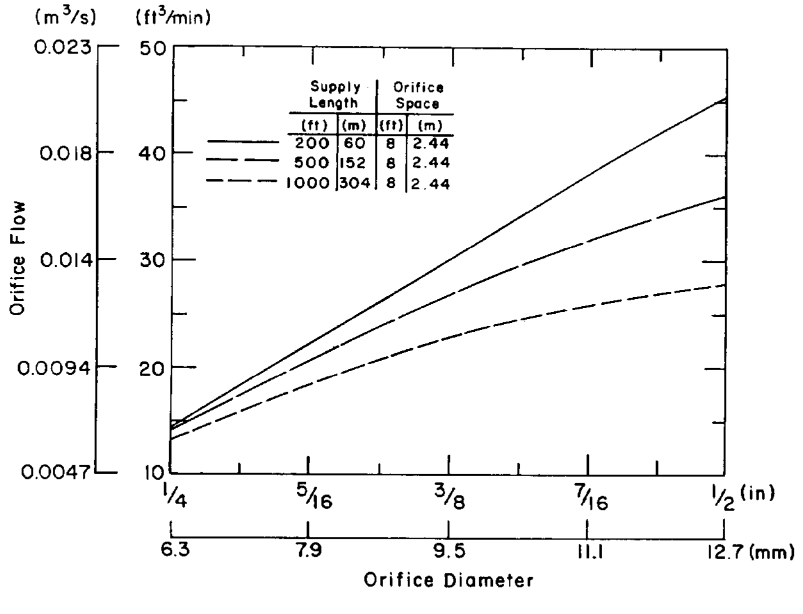


Figure 6-21. Performance curves for an air screen, showing the average air discharge from each orifice plotted with respect to orifice diameter, for three supply-line lengths. The 2.5-in. diameter, 96-ft long manifold is typical for a 110-ft wide lock, and has 13 orifices at 8-ft spacings, 20 ft below the water surface.

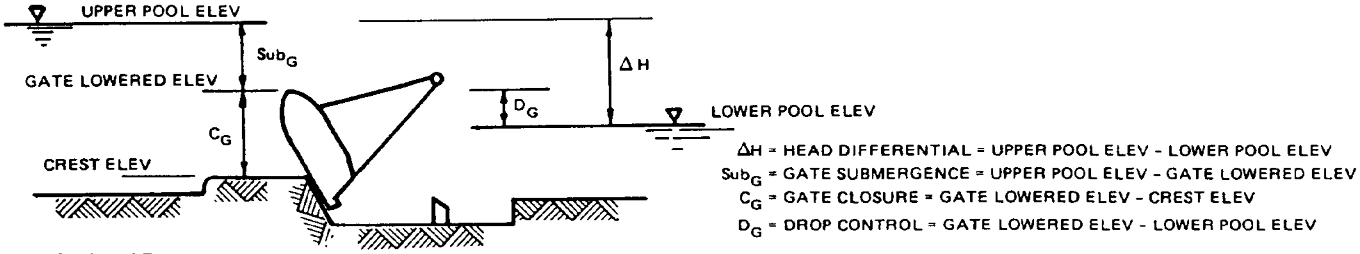
pressure, and submergence depth. The output from the program lists: hydrostatic pressure, calculated output pressure, calculated compressor discharge, friction drop in diffuser line, friction drop in supply line, and excess dead-end pressure. To illustrate how changes in the system parameters affect the operating characteristics, Figures 6-20 and 6-21 show the effect on changes in the flow through an orifice with respect to changes in orifice diameters.

6-11. Flow Inducers. A common technique to. move ice in and around the lock is the use of a towboat's propeller wash to induce a flow that moves the brash ice. The towing industry assists itself and the Corps lock personnel on occasion; towboats break away from their tows and flush sections of a navigation project. Another type of flow inducer used in the past, a submergible mixer, develops a flow in the top layer of the water to aid in moving debris or floating ice. An example of this operation formerly existed at the Chicago Harbor Lock, where submergible mixers were attached near the sector gates. However, they have been removed. To prevent ice from accumulating in front of lock miter gates that are not functioning during the winter months, several Districts have made use of commercially available flow inducers designed for the marina industry for protecting docks.

Section III. Ice Passage Through Dams

6-12. General. The question of holding ice or passing ice from one navigation project to the next is a subject of great concern on all river systems. A definitive position on this problem cannot be taken. It is clearly understood that growing a stable ice cover will reduce the overall quantity of ice grown because of the reduction in frazil generation. However, the broken ice within the frozen ship track has to be dealt with every time a vessel passes through. Just upstream of the locks is a particularly unfavorable spot to allow ice to accumulate. Almost every lockmaster will state that he wants to keep that zone above his lock clear. The specific policy, however, will have to be addressed in each of the river systems.

6-13. Submergible Tainter Gates. A case study of use of submergible gates at Corps projects was prepared by the Louisville District (U.S. Army 1985). Each of the project sites discussed in the study has a variety of dam gates. The use of submergible gates to pass ice in the North Central Division is encouraged, whereas the Ohio River Division does not allow the existing submergible gates to be operated. The specific problems and comments regarding the varied use of submergible gates are well documented in the Louisville report. Figure 6-22 summarizes many of the submergible gates considered in the study. A recent rehabilitation project on the Illinois Waterway installed submergible gates at Marseilles Dam specifically for improving ice passage. The major problem with passing ice is having sufficient water flow in the river system to open the gates, while maintaining adequate river stage. If broken ice is flowing toward the dam and the gates can be opened, a submergible gate will pass more ice than a nonsubmergible gate, given the same conditions. But it is more common that there is insufficient surface velocity to move ice toward the gate area. When this is true, the better ice passage characteristics of submergible gates provide no benefit. Moreover, ice bridging upstream of the gate, between the dam piers, is a common



Lock and Dam (COE District)	*River*	*ΔH*	*Sub_G*	*C_G*	*D_G*	*Problem*	*Remarks*
Greenup (Huntington)	Ohio	32.0	7.0	28.0	25.0	Yes	Problem: stilling basin and sill erosion and vibration Solution: submerged operation eliminated, plans and specs for modification as of Dec 1978
Meldahl (Huntington)	Ohio	30.0	7.0	28.0	23.0	Yes	Problem: stilling basin and sill erosion and vibration Solution: submerged operation eliminated
Markland (Louisville)	Ohio	34.0	7.0	33.0	27.0	Yes	Problem: vibration and jet through stilling basin and across end sill Solution: gate stops added and spillway curve modified. Submerged operation eliminated
McAlpine (Louisville)	Ohio	37.0	7.0	12.0	30.0	Yes	Problem: bed-material abrasion of sill Solution: submerged operation eliminated, spillway curve modified
Cheatham (Nashville)	Cumberland	26.0	7.0	19.0	19.0	Yes	Problem: vibration Solution: submerged operation eliminated, design and modification being considered
New Cumberland (Pittsburgh)	Ohio	22.6	7.0	12.5	15.6	Yes	Problem: vibration, cavitation between gate and sill, and recreational craft hazard Solution: submerged operation eliminated
Pike Island (Pittsburgh)	Ohio	21.0	7.0	20.0	14.0	Yes	Problem: excessive leakage Solution: submerged operation eliminated
L&D no. 4 (Pittsburgh)	Monongahela	16.6	7.0	12.5	9.6	No	Movable crest or piggyback gate
Maxwell (Pittsburgh)	Monongahela	19.5	7.0	19.0	12.5	No	Movable crest or piggyback gate
L&D no. 11 (Rock Island)	Mississippi	11.0	8.0	12.0	3.0	No	13 gates
L&D no. 12 (Rock Island)	Mississippi	9.0	8.0	12.0	1.0	No	7 gates
L&D no. 13 (Rock Island)	Mississippi	11.0	8.0	12.0	3.0	No	10 gates
L&D no. 16 (Rock Island)	Mississippi	9.0	8.0	12.0	1.0	No	3 of 15 gates
L&D no. 17 (Rock Island)	Mississippi	8.0	8.0	8.0	0.0	No	8 gates
L&D no. 18 (Rock Island)	Mississippi	9.8	5.0	15.0	4.8	No	14 gates
L&D no. 20 (Rock Island)	Mississippi	10.0	3.0	17.0	7.0	No	6 of 40 gates
L&D no. 21 (Rock Island)	Mississippi	10.5	8.0	12.0	2.5	No	10 gates
L&D no. 22 (Rock Island)	Mississippi	10.5	8.0	17.0	2.5	No	1 of 10 gates
L&D no. 24 (St. Louis)	Mississippi	15.0	8.0	17.0	7.0	Yes	15-80 ft TG's, vibration, stress on trunion; submerged operation eliminated
L&D no. 25 (St. Louis)	Mississippi	16.0	7.0	18.0	9.0	Yes	14-60 ft TG's. vibration stress on trunion; submerged operation eliminated
L&D no. 26 (St. Louis)	Mississippi	24.0	3.0	27.0	21.0	No	30-40 ft TG's

Figure 6-22. Summary of submergible gates and their problems (after U.S. Army 1987) Many of these were considered in the Louisville District study of the use of submergible gates for passing ice (U.S. Army 1985).

problem. However, a benefit of using submergible gates is that, since the gate is kept under the water, many gate freezeup problems are eliminated.

6-14. Roller Gates. Roller gates are used extensively on the Mississippi River. At some projects they are lowered to a fixed submerged setting in the late fall, and are kept in that position for the duration of the winter. The pools are then maintained by adjusting tainter gates. At other projects, the tainters are left to freeze in and the roller gates are adjusted, either submerged or with a bottom opening, to maintain upper pool stages. (At Lock 10 in the St. Paul District, the roller gates are not designed to be submergible, but they are the operative gates in winter.) In the cases where the roller gates are used in the submerged mode in winter, they may assist in ice passage, functioning in the same manner as submergible tainter gates, but having the same limitations. Other problems associated with roller gates are largely related to the lifting mechanisms, in which ice interferes with lifting chains, guide channels, and gear racks.

6-15. Conventional Tainter Gates. The openings required for ice passage at conventional tainter gates are usually quite large owing to the very high flow velocities needed to sweep floating ice downward to the bottom openings. As a result, except during periods of flood flow, these large openings normally cannot be used because of the likelihood of downstream scour at low tailwater stages. Thus, during the customary low-flow conditions of the winter season, ice passage at these gates is not feasible.

6-16. Gate Limitations in Winter. As detailed in Chapter 3, Paragraphs 3-3a (7) through (9), successful operation of dam gates in winter, regardless of gate types, is impeded by accumulated forebay ice, by ice buildup on gate and pier structures from spray and splashing, and by the freezing of leakage past gate seals. All of these factors combine to render ice passage through gate bays very difficult and unreliable, unless remedial measures as discussed in the following section are employed.

6-17. Other Ice Passage Schemes. Ice can be successfully passed at some navigation locks having auxiliary lock chambers and bulkhead lift systems by skimming the ice over partially raised bulkheads. Figure 6-23 shows such an operation. This appears to be an effective way to pass ice through the lock system, thus clearing the upper approach area.

Section IV. Lock and Dam Deicing

6-18. General. As described in Chapter 3, the ice-related problems at navigation structures are severe during the winter months. Exposed mechanically operated systems may be frozen-in and become inoperable. The weight of ice formed on structures that need to be lifted or moved may become excessive so that the system becomes overloaded. Ice loads can also cause structural damage. Icing on the recess walls or gates of navigation locks prevents full opening of the gates. Ice formation on the chamber walls prevents full use of the lock width. Ice in any form causes safety hazards for personnel working on or near it. All of these ice problems involve ice formation on or adhesion to critical surfaces at locks and dams. Solutions to these ice problems at navigation

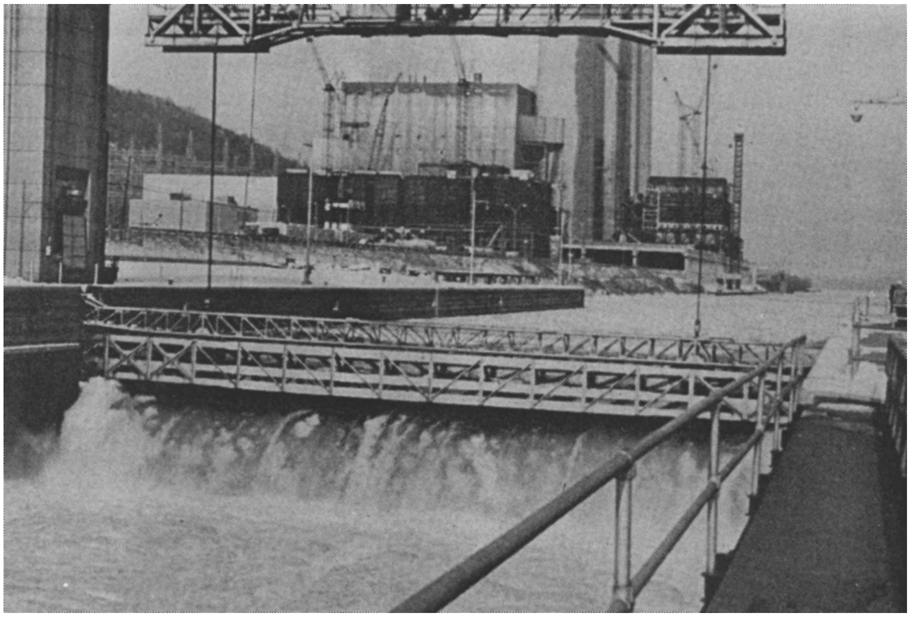


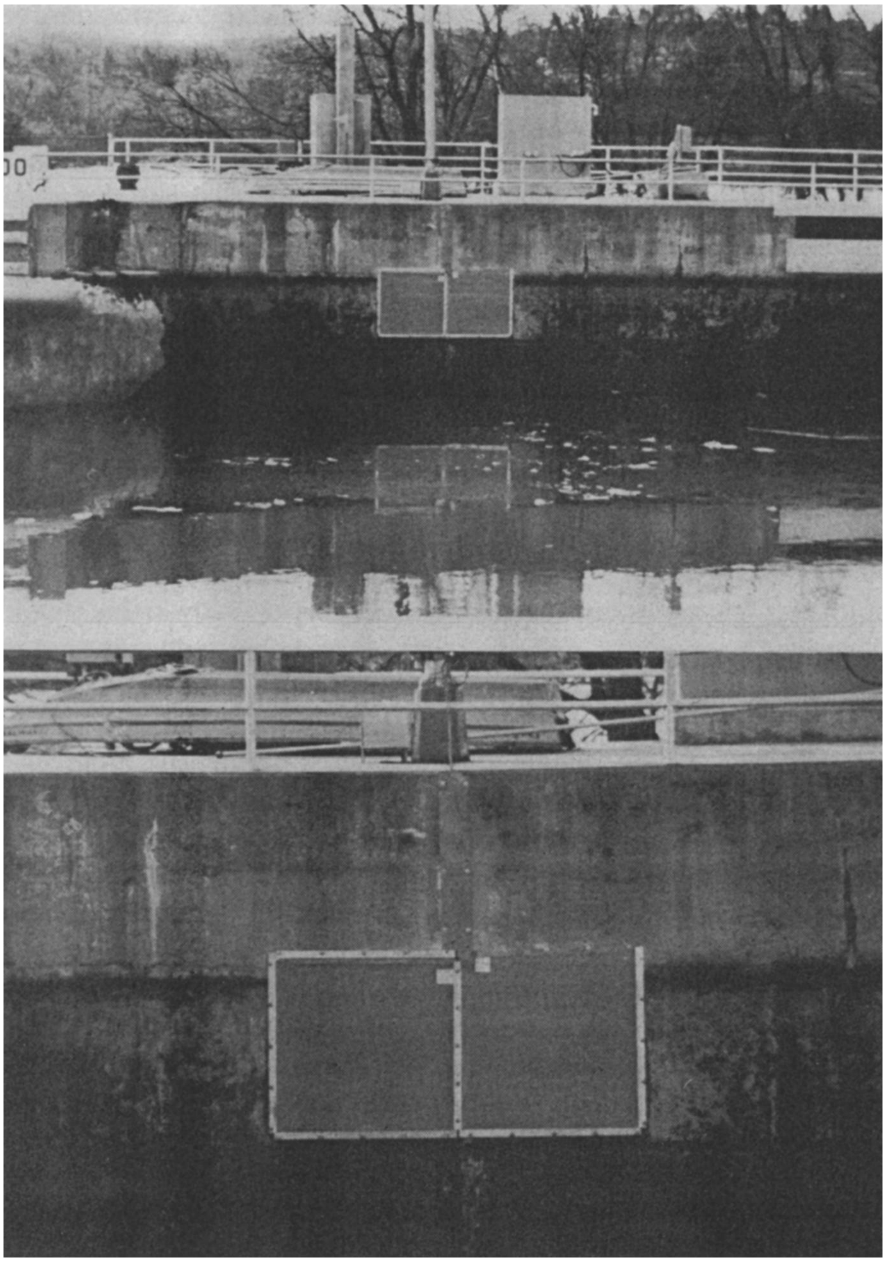
Figure 6-23. Ice passage at New Cumberland Lock on the Ohio River. The partially raised bulkhead of the auxiliary lock chamber allows flow to carry ice out of the lock approach area.

projects currently are time-consuming and expensive. This section addresses several approaches to solving the problems of surface ice formation and adhesion.

6-19. Thermal Measures Against Wall Icing. Ice adhesion on walls can be prevented by maintaining wall temperatures above 32°F, or ice collars can be shed periodically by raising the wall temperature intermittently. Possible arrangements include embedded (but removable) electrical heating cables within walls, direct placement of heat mats on walls, and heating dam gate side J-seals.

a. Embedded Electrical Heaters. The use of embedded electrical heaters that cannot be removed for replacement without major rehabilitation is *not recommended.* Almost every navigation project that has installed embedded electrical heaters has some heaters that have failed and cannot be replaced. The recommendation for those areas where embedded heaters are needed is a replaceable heat tape as described here. During a rehabilitation project, where the concrete walls are to be resurfaced, 3/4-in.-diameter stainless steel pipes should be installed, 6 to 8 in. on center, with the bottom ends sealed. At the top of the pier or along the top of the wall, the top ends of the pipes are accessible so that electrical leads can be run from one vertical pipe to the next. The tubes are filled with glycol to act as a heat-transfer fluid, once the self-regulated heat tape is inserted into the pipe. The heat tape can be cut to specific lengths by project personnel and inserted into the pipe. The heat tape is self-regulating and has an output of 37 W/ft at 32°F. In the control circuit, timers and thermostats can be added to limit power consumption. If a heat tape fails, then a new length of heat tape may be cut and installed. The cut end should be sealed using heat-shrink tubing, and a cold electrical lead is added to the upper end. Alternate techniques of installing the pipes are by drilling vertical holes along the edge of a pier or wall (however, a major concern is the possibility of the hole breaking out) and by cutting vertical slots 3 to 4 in. deep in the wall.

b. Wall Heat Mats. Fiberglass-reinforced plastic heat mats have been placed directly on a vertical concrete wall at a lock to prevent ice from forming a collar in the gate recess area. The commercially available mats can be provided in any shape or size up to 4 x 8 ft. Variable power ratings are also available. The mats shown in Figure 6-24 are 100 W/ft^2. These panels are each



a. General view.

b. Detail showing plate over vertical groove in wall above heat mats, which contains electrical leads.

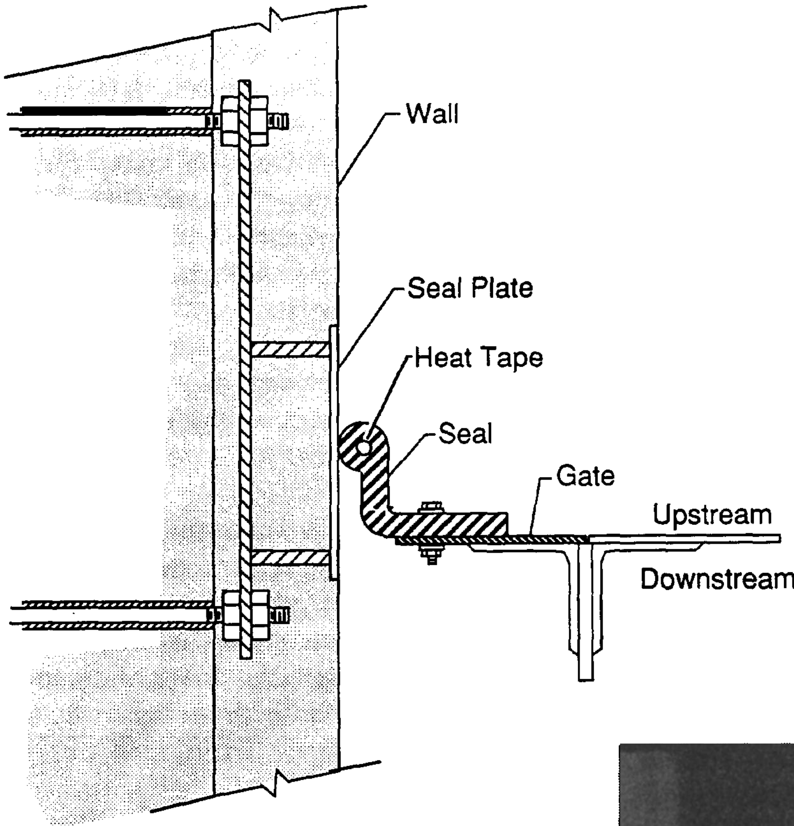
Figure 6-24. Fiberglass-reinforced plastic heat mats installed on a miter gate recess wall at Starved Rock Lock on the Illinois Waterway.

4 x 4 ft x 1/4-in.-thick. The mats are very effective in keeping the wall clear of ice. Material costs (1988) for such a mat material are about $70/ft^2.

c. Heated J-Seals on Dam Gates. Heating the side J-seals improves their ability to reduce leakage past tainter gates, and thus reduce the associated buildup of icing on the walls and the gate structures. This method is easily adaptable at low cost to existing dam gates (using Huntington J-seal Mold no. 3493 or equivalent). This in-situ heating system has been made up so that it can be inserted into the hollow channel of a J-seal; it keeps ice from forming on the seal and increases the flexibility of the seal at lower temperatures. With increased flexibility, the seal better conforms to irregular surfaces, thereby reducing leakage to the downstream side. With little or no leakage, ice formation on the cold, exposed downstream side is substantially reduced. Neither steaming nor "cindering" (i.e., pouring cinders in the water above the locations of the greatest leakages, so that the cinders flow toward the leaks and plug them) were required during tests of the in-situ heating system at Starved Rock Lock and Dam on the Illinois Waterway, where it was installed during a recent dam rehabilitation. The self-regulating heat trace tape, 208 V ac at 37 W/ft at 32°F, was cut from a spool to a length of 18 ft. The heat tape was sealed at one end. The other end had a cold electrical lead attached to connect to the electrical power. The J-seal and the inserted heater are shown in Figure 6-25. The 1988 cost of Huntington J-seal Mold no. 3493 is $14.50/ft. The seal is currently manufactured by Buckhorn Rubber, 55 W. Techne Center Drive, Milford, Ohio 45150 (800-543-5454). The self-regulating heat trace tape is widely available at an approximate 1988 cost of $5/ft. If both seals of a gate are heated and the heaters are operating at maximum power, the operating cost per day is $2.24, assuming 1332 W at $0.07/kWhr. Use of heated J-seals would not preclude the inclusion of embedded electrical heaters in gate pier walls in rehabilitations or new designs, because embedded heaters aid in keeping seal plates ice-free above or below the immediate seal-contact area, so that gates can easily be placed in any chosen position.

6-20. Surface Treatments to Reduce Ice Adhesion. There is a long history of study in this area for a variety of applications, but surface treatments that shed ice reliably and repeatedly have not yet emerged. The only chemical treatment that has been used successfully on a large scale for truly shedding ice is repeated application of chemicals that depress the freezing point of water. As far as concrete surfaces are concerned, the classic treatment for ice removal is repetitive application of sodium chloride or calcium chloride. Another ice control method is a permanent or semi-permanent chemical coating that reduces the adhesive force between the coated surface and the ice that forms on it. The ideal material would be one that prevented ice formation entirely. No known coatings do this, but some make the task of ice removal from coated surfaces easier.

a. One successful material is a long-chain copolymer compound made up of polycarbonates and polysiloxanes. The most effective coating of the many that have been tested is a solution of polycarbonate-polysiloxane compound, silicone oil, and toluene. The mixture is highly volatile and leaves a thin coat of the copolymer and silicone on the surface to which it is applied. The surface to be coated must be clean and dry. For concrete and metal surfaces (bare and painted); steam cleaning is sufficient; however, a detergent may be added to the water of the steam cleaner. This was done, for example, in one case where navigation lock walls were heavily coated with oil



a. Diagram.

b. Heat tape installed in the hollow channel of a J-seal.

Figure 6-25. J-seal installation on tainter gate.

and algae. Once the surface is clean and dry, the solution can be sprayed on using an airless spray gun system. A single pass will deposit a coat 1 to 2 mils thick. Three coats are recommended for a coating thickness of about 5 mils. Achieving this final thickness requires about 6 gal/1000 ft^2. Care has to be taken when mixing the solution. Toluene is a combustible material, so no electrical motor-driven mixer should be used. An air-operated drill motor fitted with a rod with mixer blades has worked satisfactorily. The fumes may also be a health hazard, so that a well-ventilated mixing area should be used. A 55-gal. drum fitted with a bracket to hold the drill motor is a suitable mixing container. Batches of up to 40 gal. can easily be handled. The liquid portions, toluene and silicone oil, are placed in the container first. Then the mixer is started and the copolymer powder is slowly added. Mixing continues until all solids are dissolved. Then the solution can be transferred to a storage container. Tests to determine the merits of an undercoating for the copolymer (on concrete surfaces that are worn and rough) show that an epoxy-type coating that acts as a filler over the rough concrete provides a better surface to which the copolymer adheres.

b. Commercially available two-part epoxy coatings, which can be applied in wet environments, have been tested for ice-phobic characteristics. Several of these coatings perform equally as well as the copolymer coating. They are far more durable since they are an epoxy resin and a polyamine-based curing agent. The epoxy coating gives concrete ideal protection against the ingress of chloride ions, carbon monoxide and other corrosive agents over the design life. The hard, smooth finish provides a very low friction coefficient, thus reducing the bond strength between ice and substrate.

c. Cladding of wall surfaces by materials that shed ice easier than concrete is another approach to solving the problem of ice adhesion. In a demonstration at Starved Rock Lock in Illinois, a 4 x 8 ft x 1/2-in.-thick sheet of high-density polyethylene was fastened to the curved part of the gate recess wall at the quoin end, at the ice-collar level. Hilti studs, 20 in. on center, were used for attaching the sheets. Ice formed on the polyethylene surface and the concrete surface equally, but far less effort was needed by lock personnel to manually remove the ice from the plastic material, because of the lower adhesion forces between the polyethylene and the ice. Problems were noted with ice being more difficult to dislodge where the studs protruded, but a redesigned fastening technique could overcome that problem. The polyethylene is not highly durable when pike poles or ice chippers have to be used extensively, though. The use of steam to dislodge the ice collars would eliminate the risk of this damage. The panels are easily and economically replaced, since their 1988 cost was only about $7/$ft^2$.